University of Strathclyde Engineering

A new platform for validating real-time, large-scale WAMPAC systems

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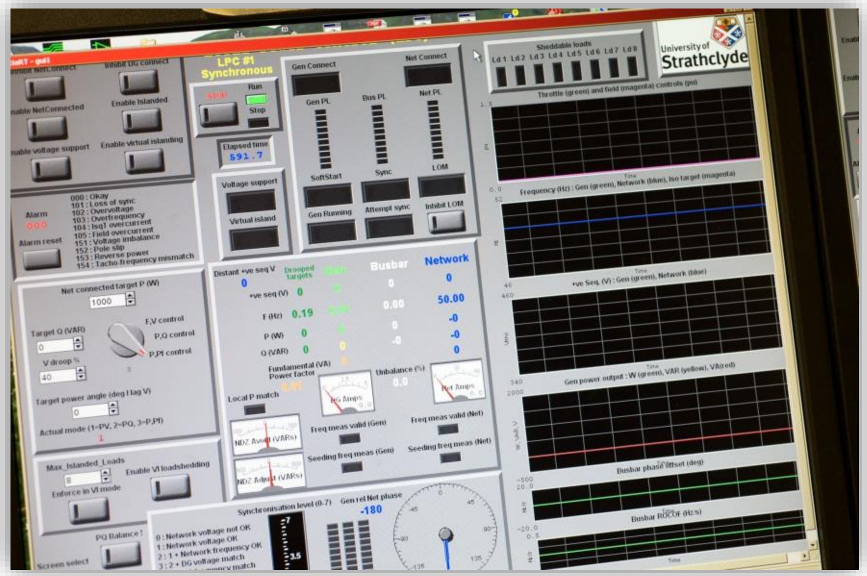
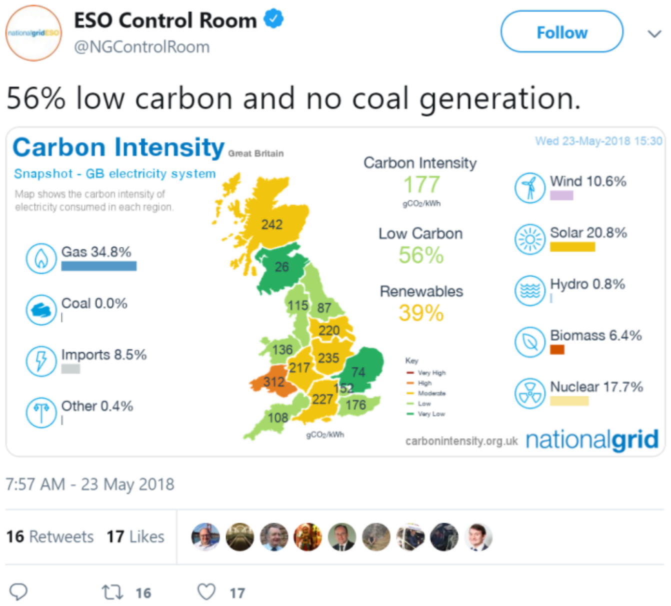
Overview

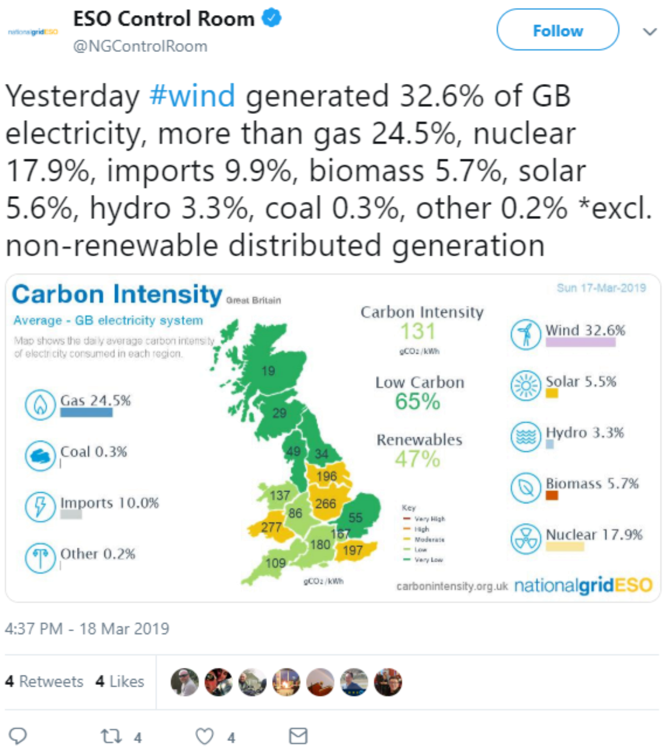
- Industry position and challenges
  - Renewable energy trends
  - Reduced system inertia
- Using GTFPGA for 64 PMUs
- Hardware and software design
- Monitoring interface and automation
- Reporting latency analysis
- Next steps



UK energy situation

Trend of reduced conventional synchronous generation





April 2017
First no-coal day since Industrial Revolution

April 2018
Three consecutive no-coal days

March 2019
33% wind contribution – common throughout March

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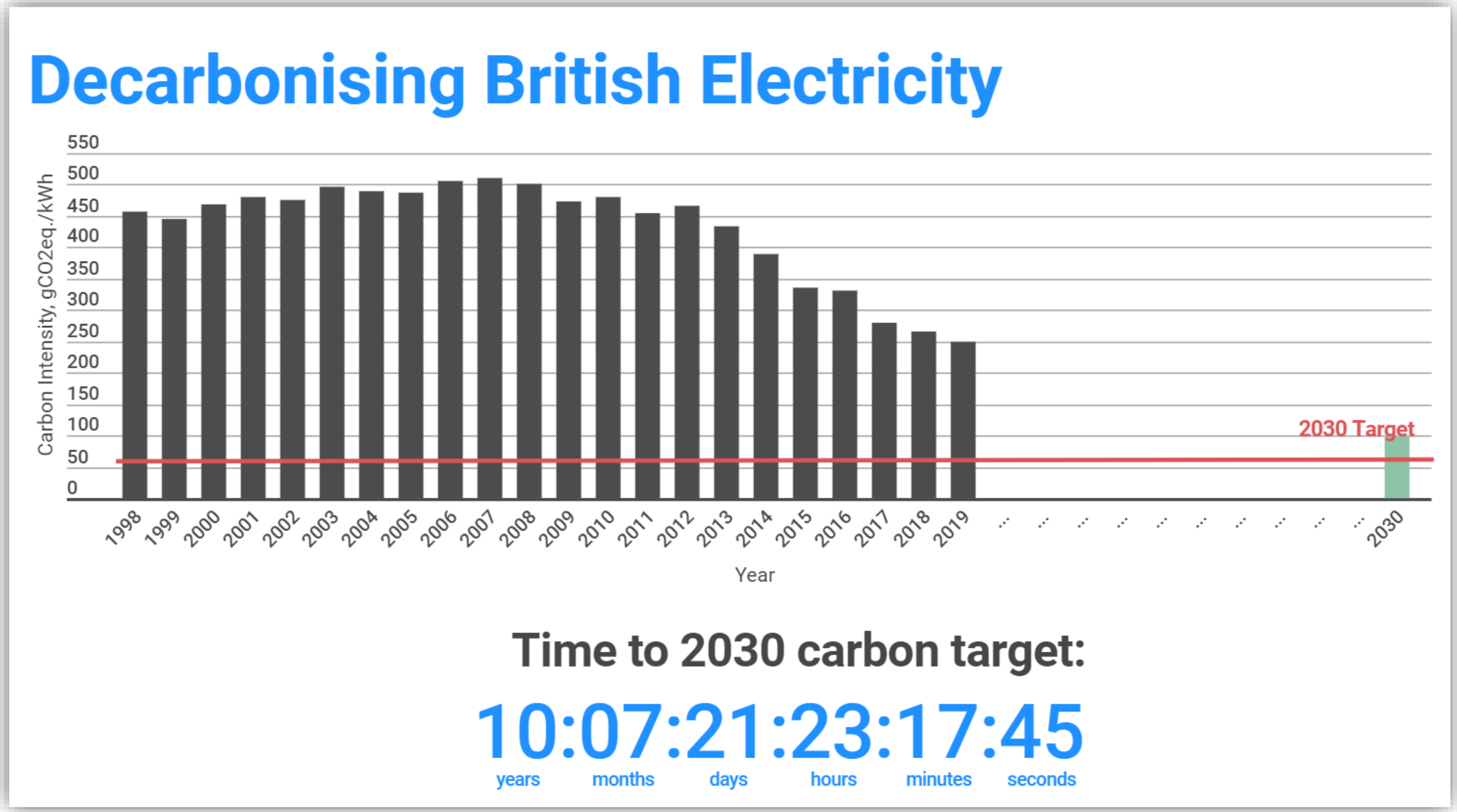
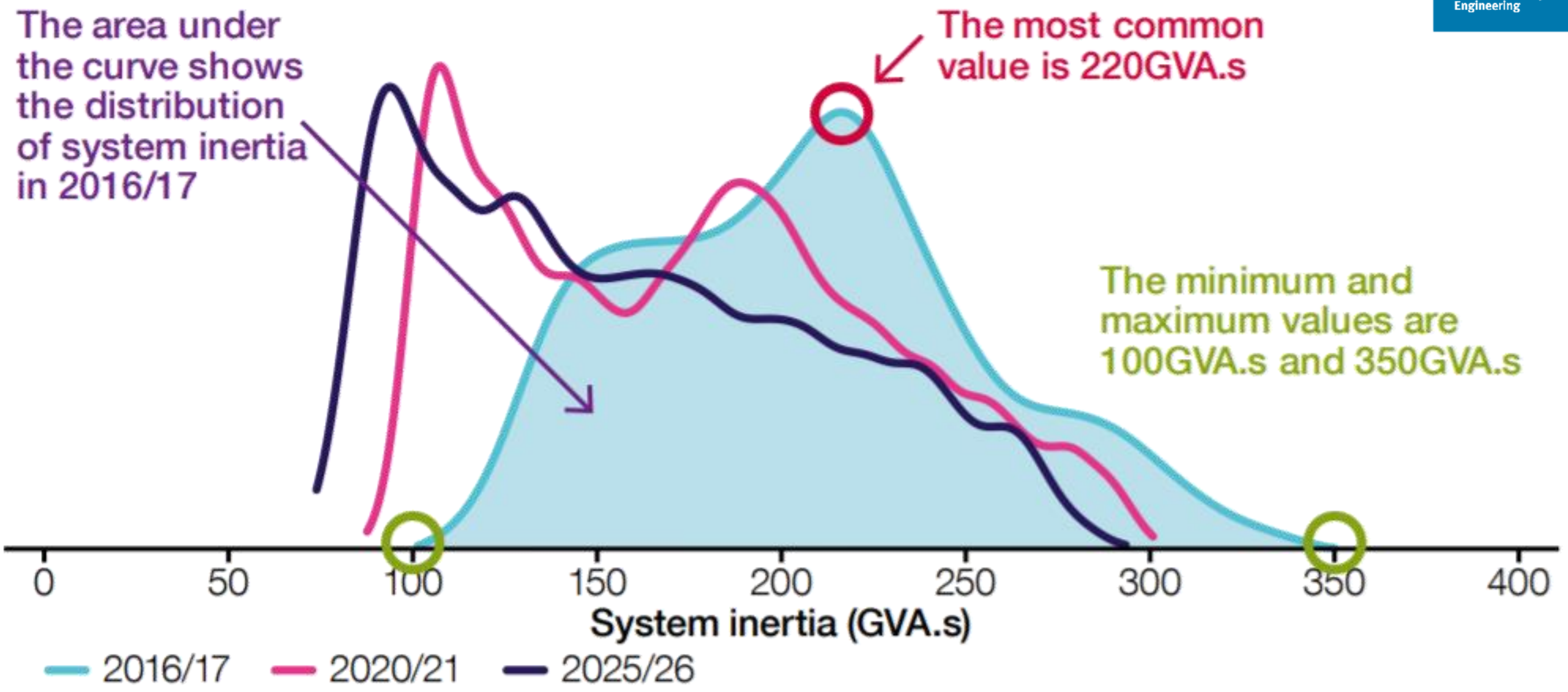
Actually approaching our target...



https://www.mygridgb.co.uk/dashboard/

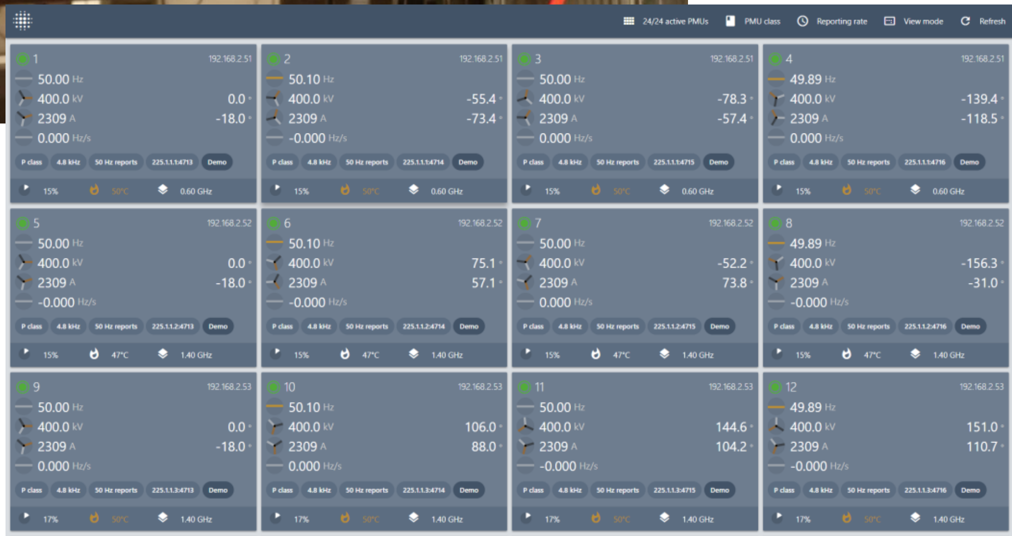
UK: reducing system inertia



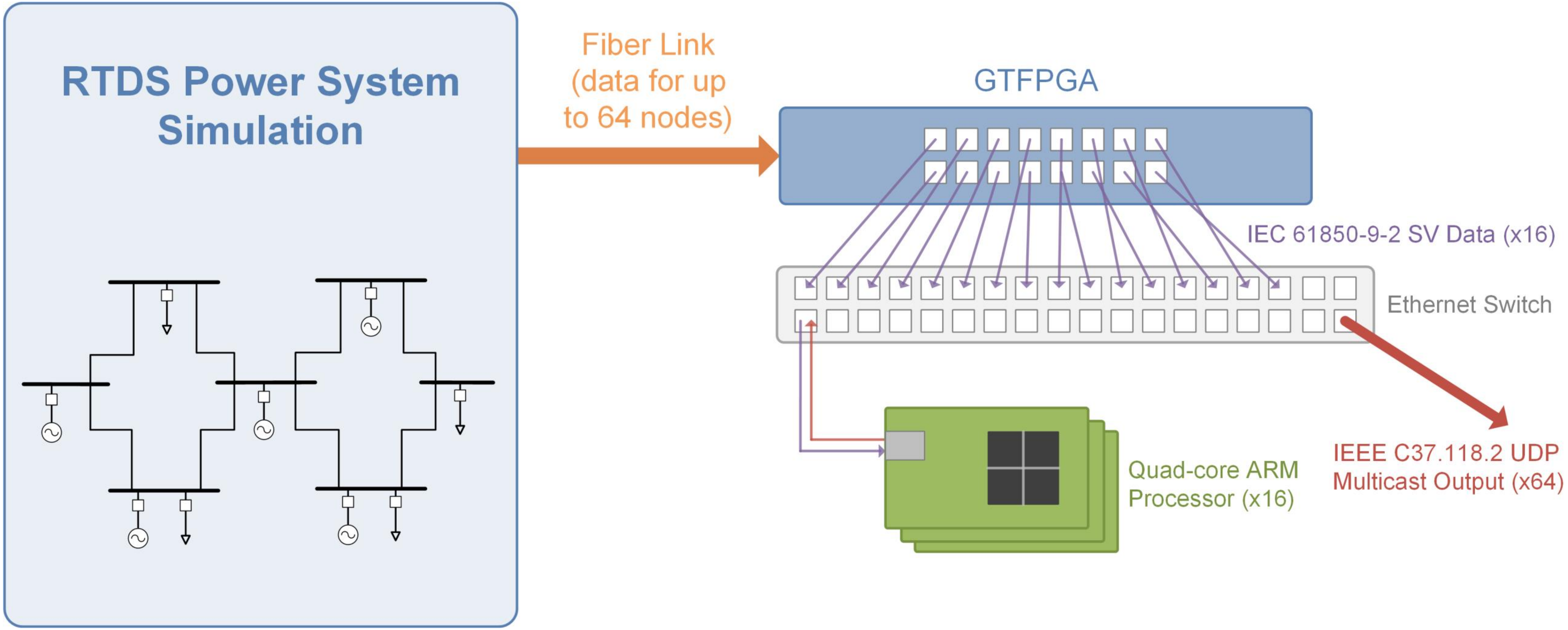
From National Grid System Operability Framework 2016

Large-scale PMU testbed

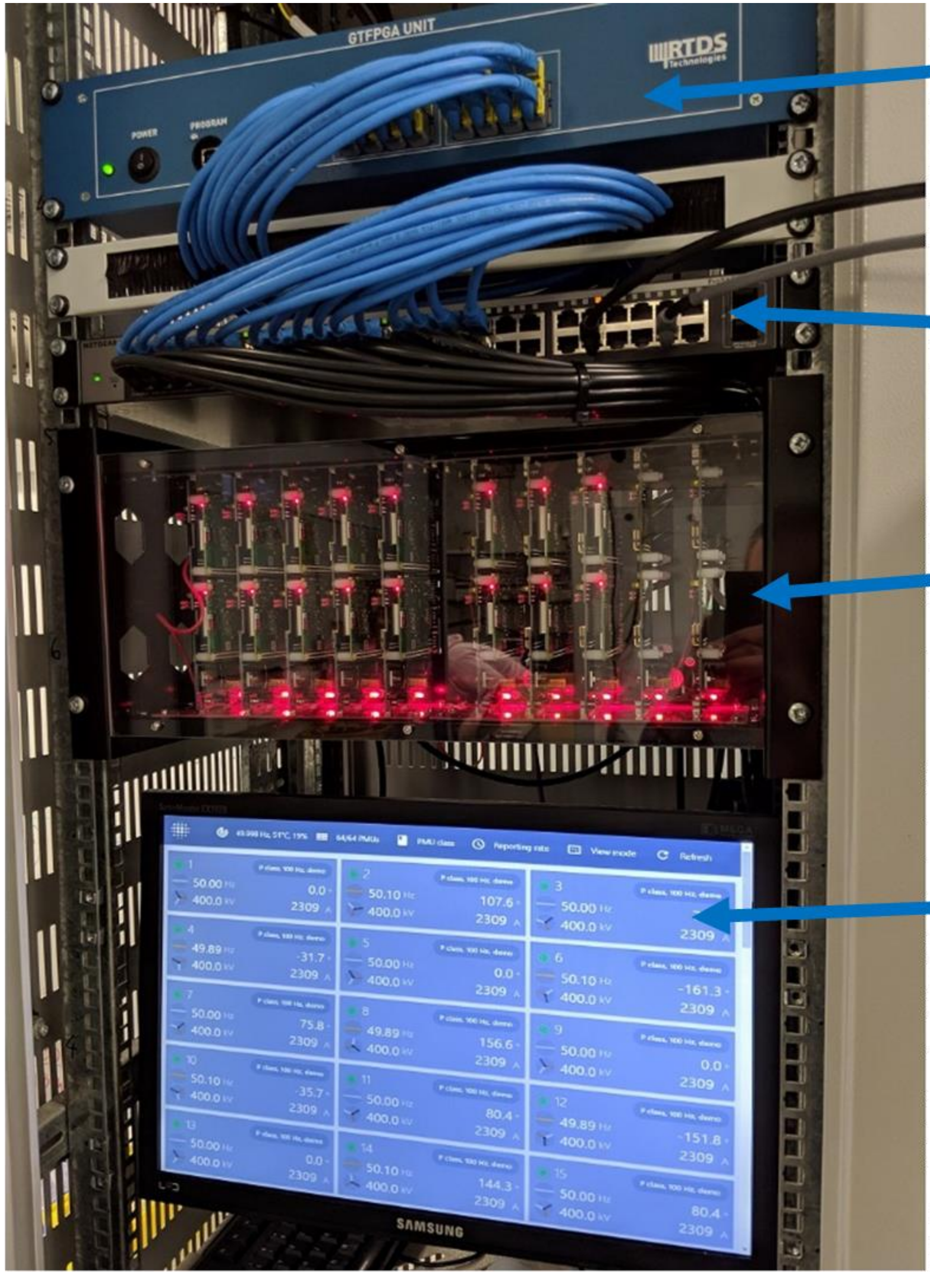
- RTDS GTFPGA
- 16x Raspberry Pis
- Strathclyde PMU algorithm
  - Adaptive filter window
- **64 PMUs in real-time**
- Dynamically change reporting rate, M or P class



Hardware design



Hardware design



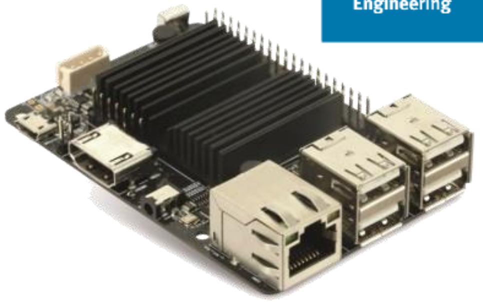
GTFPGA

Ethernet Switch

Cluster of 16 ARM Processors

Web-based Management Interface

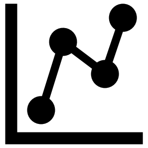
ARM processor and OS choice



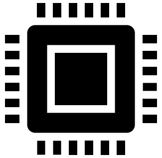
Hardware	Raspberry Pi 3 B+	Raspberry Pi 3 B+	Odroid C2
Operating System	Raspbian Stretch Lite	**DietPi**	**DietPi**
CPU	Quad-core Cortex-A53	Quad-core Cortex-A53	Quad-core Cortex-A53
Maximum CPU clock	1.4 GHz	1.4 GHz	**1.5 GHz**
Memory	1 GB	1 GB	2 GB
Ethernet	Gigabit, but implemented over half-duplex USB interface	Gigabit, but implemented over half-duplex USB interface	**Gigabit**

Software design

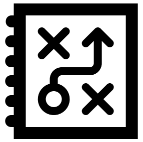
- Using **4800 Hz** sampling rate for SV data
  - Up to 24 values => 4x three-phase voltage and current (per Ethernet frame)
  - Two ASDUs (samples) per frame (so 2400 packets/s)



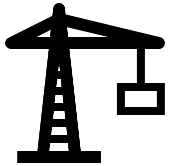
- One PMU algorithm running per ARM core
  - 64 cores => 64 PMUs
  - Using “rapid61850” library to decode SV
  - Using OpenMP to execute parallel code sections



- Use of VLANs to precisely control all SV and C37.118.2 data flows



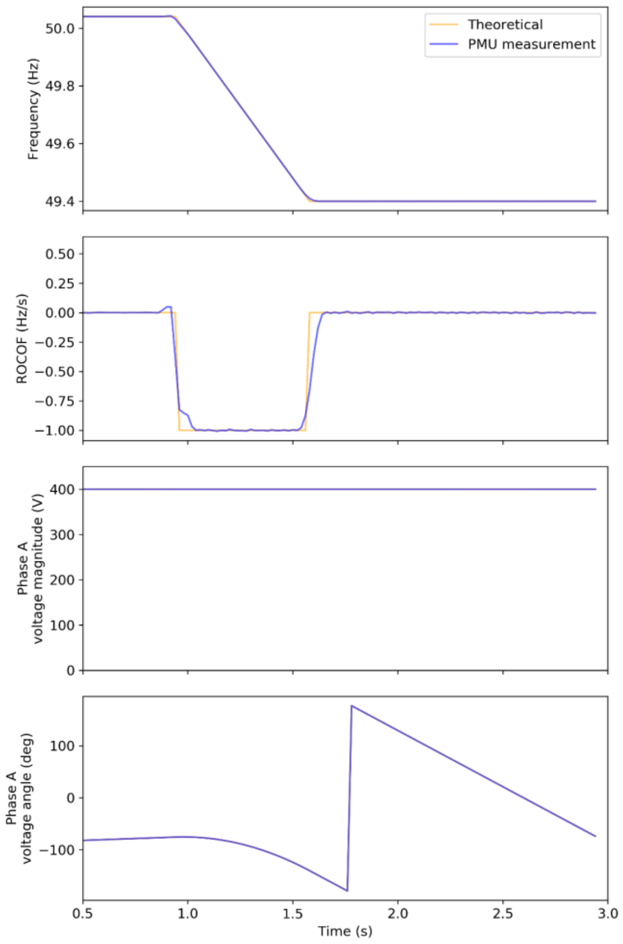
- Python scripts to automate Pi configuration



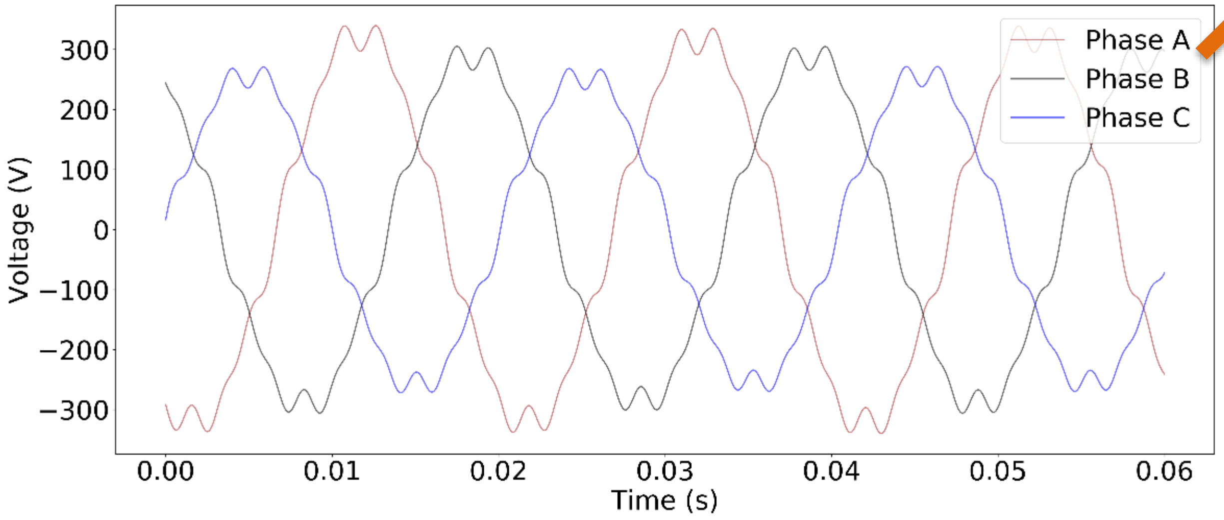
PMU algorithm choice and performance

- Highly resilient to actual grid disturbances
- 0.01% typical worst-case total vector error (TVE)
- Suited to distribution system applications
- Efficient computational performance
- M-class and P-class versions

Accurate PMU response



Emulated grid disturbance



Worst-Case M-class PMU Performance

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Test	TVE (%)	FE (Hz)	RFE (Hz/s)
Frequency Range	0.007-0.012	0.00017	0.0066
Harmonic Distortion	0.005-0.013	0.000092	0.0036
Phase Modulation	0.25	0.0086	0.34
Frequency Ramp	0.12-0.13	0.000193	0.0055

~100x better than IEEE standard requirements

Test	Response Time (ms)	Delay Time (ms)	Max over- or under-shoot (%)
+ve Magnitude Step	50.5	0.758	1.11%
+ve Phase Step	66.5	-2.5	0.68%

Monitoring interface

49.999 Hz, 54°C, 23%, 72 ms | 64/64 PMUs | Plots | PMU class | Reporting rate | View mode

1 192.168.2.51
50.00 Hz
399.4 kV -88.7 °
371 A -86.5 °
-0.000 Hz/s
M class | 4.8 kHz | 100 Hz reports
225.1.1.1:4713 | 75.414 / 78.777 ms
26% 54°C 1.40 GHz

2 192.168.2.51
50.00 Hz
399.4 kV -89.3 °
143 A -91.5 °
-0.000 Hz/s
M class | 4.8 kHz | 100 Hz reports
225.1.1.1:4714 | 75.269 / 78.788 ms
26% 54°C 1.40 GHz

3 192.168.2.51
50.00 Hz
399.4 kV -89.0 °
71 A -116.3 °
-0.000 Hz/s
M class | 4.8 kHz | 100 Hz reports
225.1.1.1:4715 | 74.839 / 78.777 ms
26% 54°C 1.40 GHz

4 192.168.2.51
50.00 Hz
399.4 kV -89.1 °
576 A -90.6 °
-0.000 Hz/s
M class | 4.8 kHz | 100 Hz reports
225.1.1.1:4716 | 74.545 / 78.772 ms
26% 54°C 1.40 GHz

5 192.168.2.52
50.00 Hz
400.1 kV -89.1 °
66 A 100.0 °
0.000 Hz/s
M class | 4.8 kHz | 100 Hz reports
225.1.1.2:4713 | 73.235 / 77.453 ms

6 192.168.2.52
50.00 Hz
399.5 kV -89.3 °
280 A 101.7 °
0.000 Hz/s
M class | 4.8 kHz | 100 Hz reports
225.1.1.2:4714 | 73.61 / 77.329 ms

7 192.168.2.52
50.00 Hz
399.5 kV -88.9 °
144 A -90.5 °
0.000 Hz/s
M class | 4.8 kHz | 100 Hz reports
225.1.1.2:4715 | 74.122 / 77.466 ms

8 192.168.2.52
50.00 Hz
400.1 kV -88.9 °
130 A -82.0 °
0.000 Hz/s
M class | 4.8 kHz | 100 Hz reports
225.1.1.2:4716 | 73.544 / 77.492 ms

Load shedding scenario – frequency change

Load shedding scenario – voltage angle

Accurate measurement PMU reporting latency

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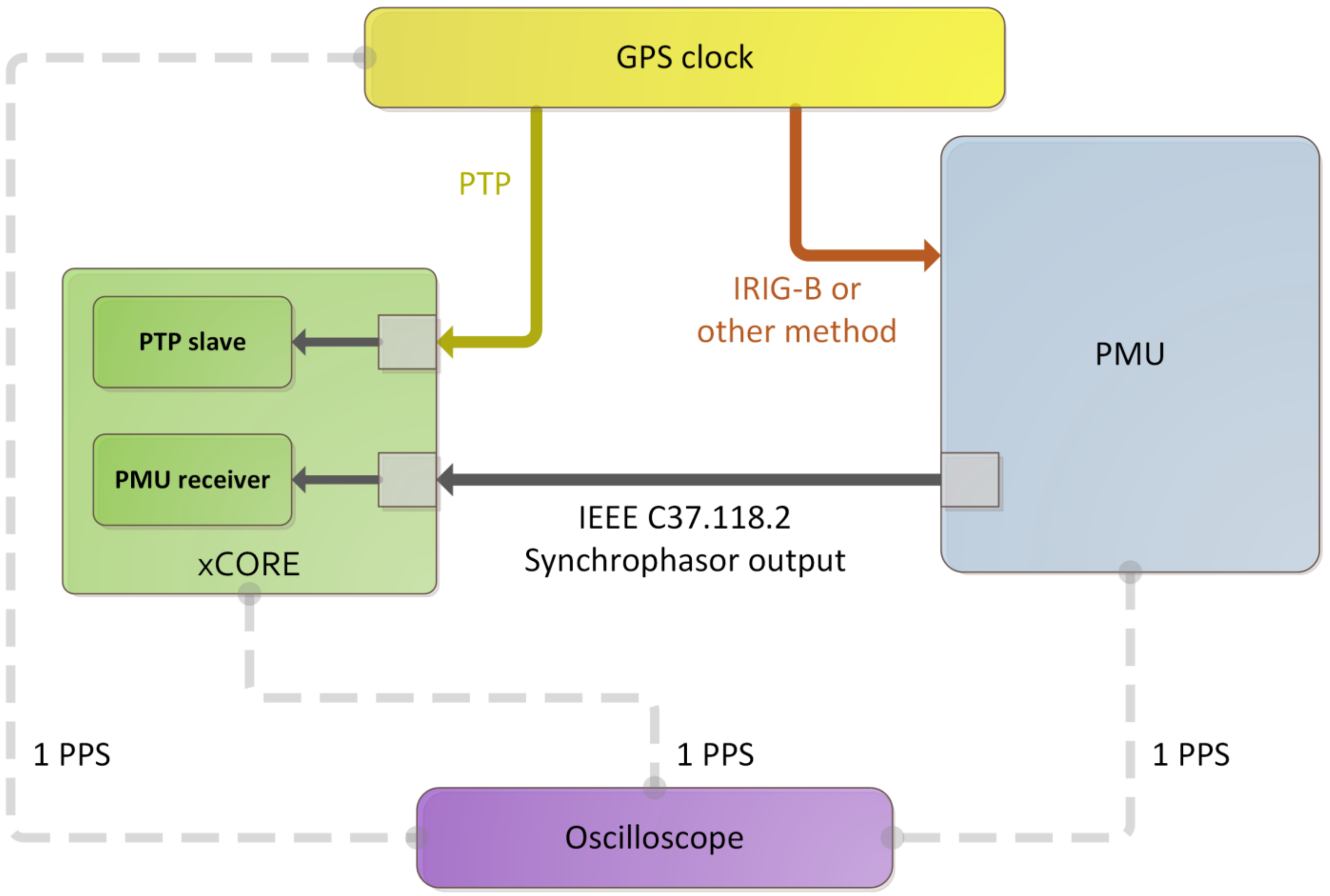
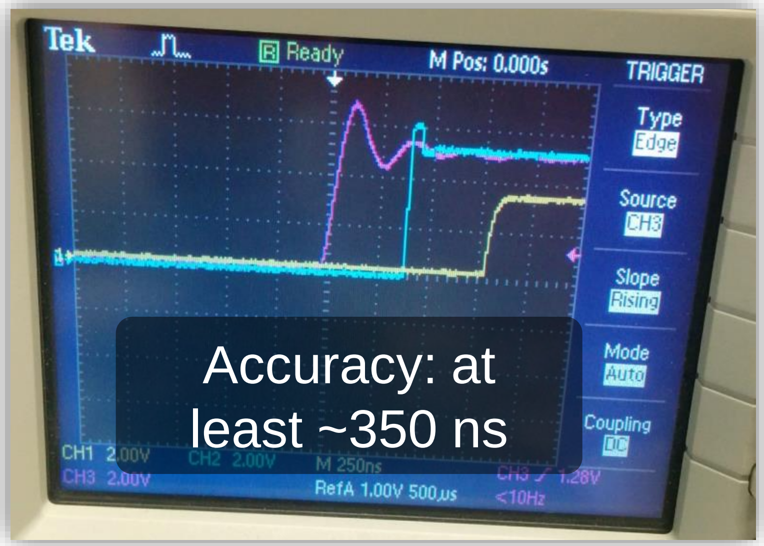


xCORE platform

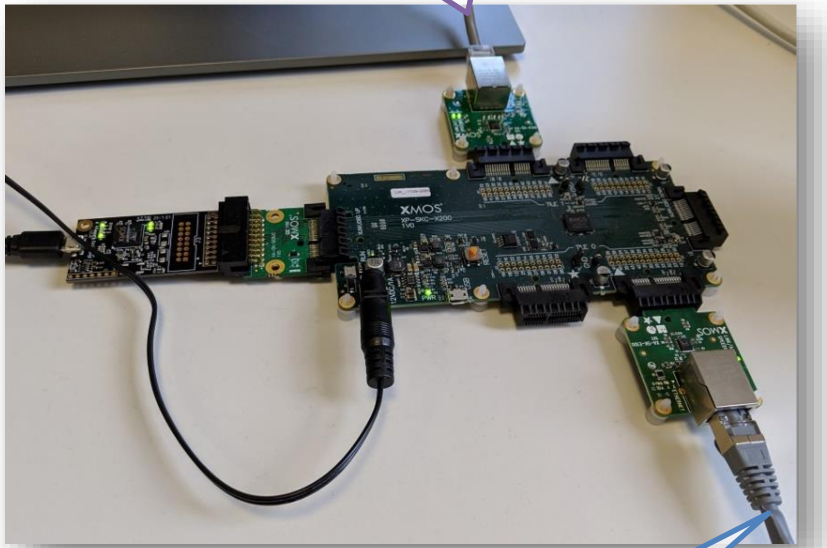


Accuracy: at least ~350 ns

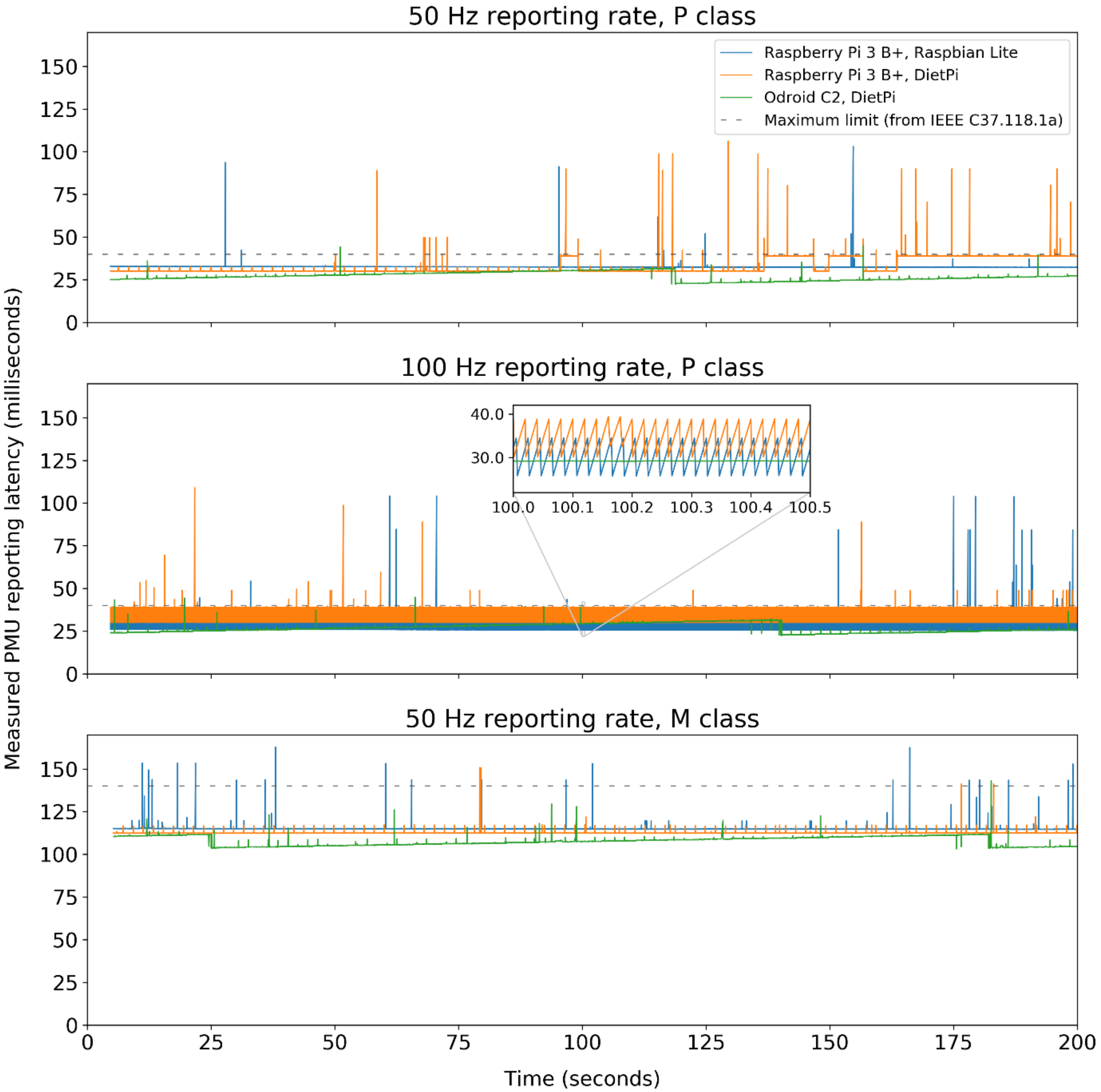
https://github.com/stevenblair/pmu-latency-measure

Reporting latency analysis

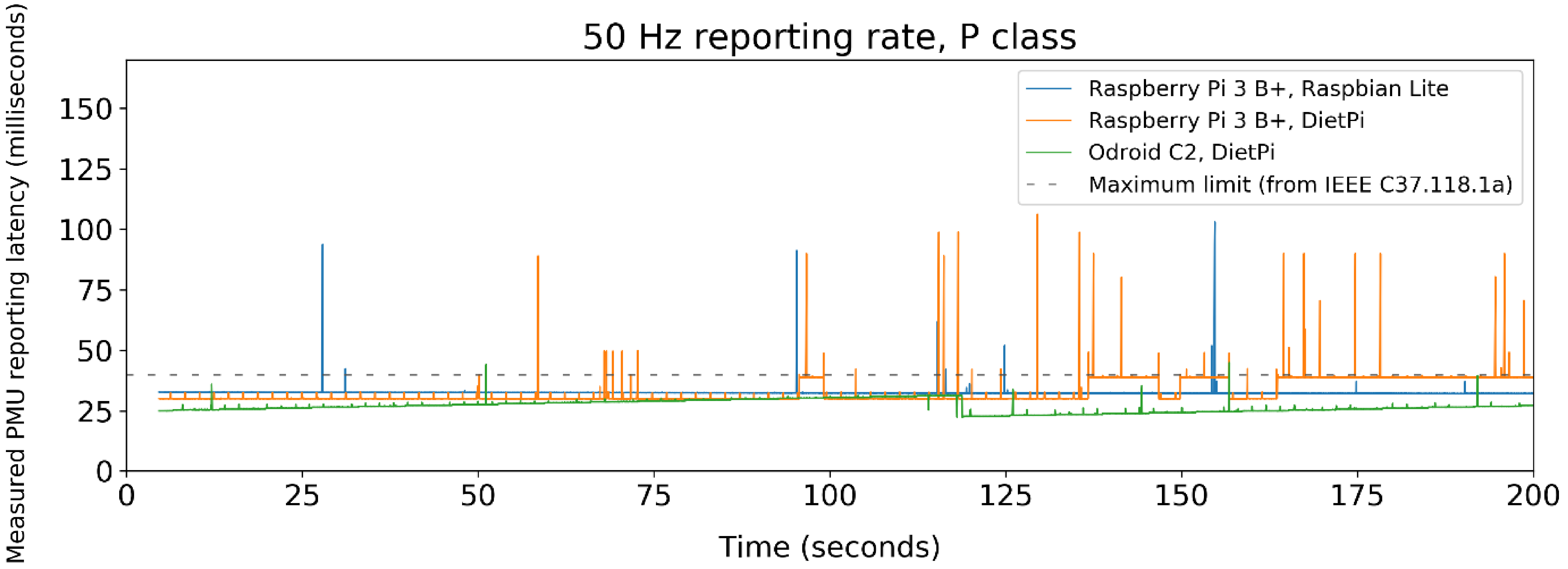
Synchrophasor outputs (x 64)



PTP time synchronisation



Reporting latency analysis



How long does a packet take from the UK to the USA?

Measured as **~60 ms** each way over SD-WAN

Linking two laboratories

Real-time SD-WAN connection

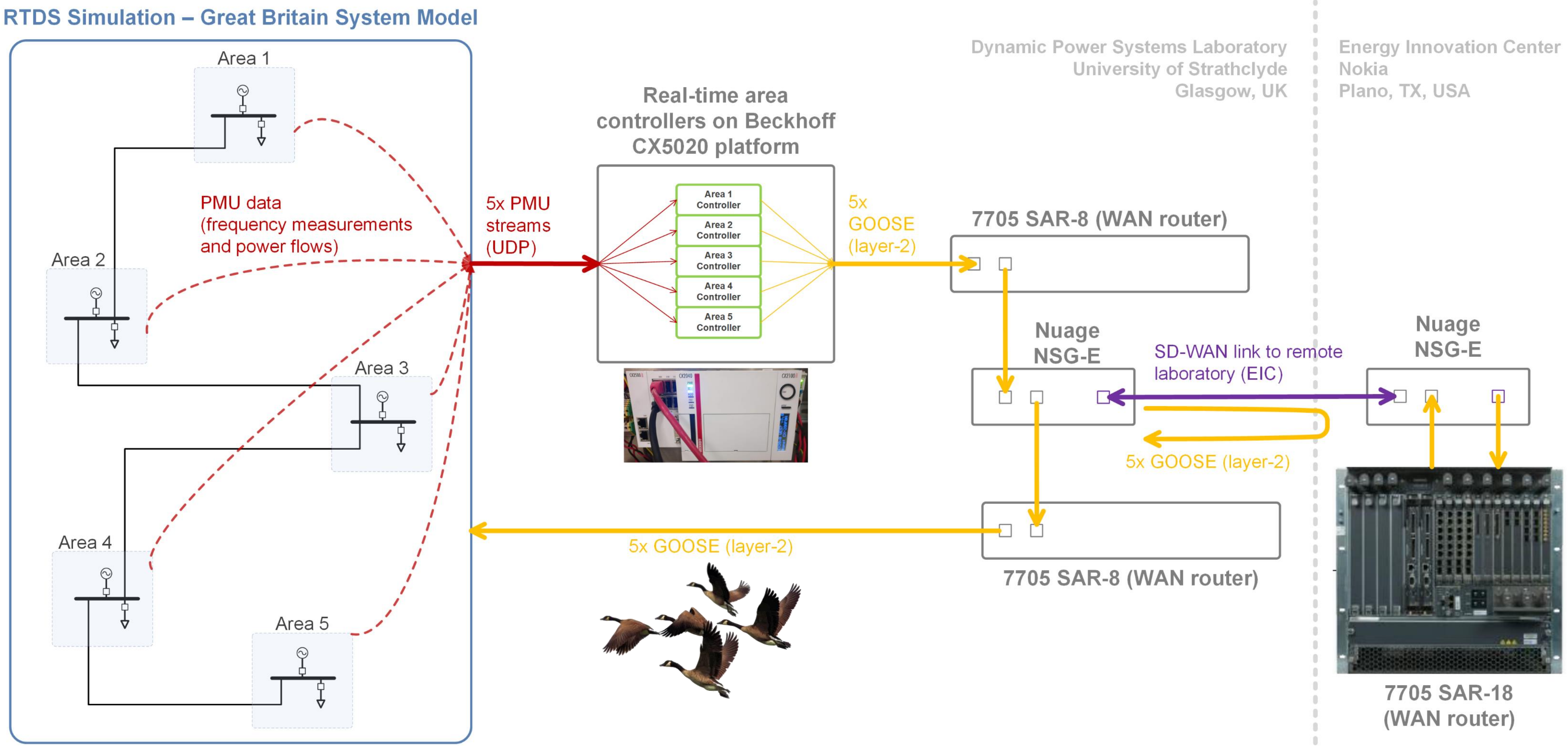
Dynamic Power Systems Laboratory

Strathclyde
Glasgow, UK

Energy Innovation Center

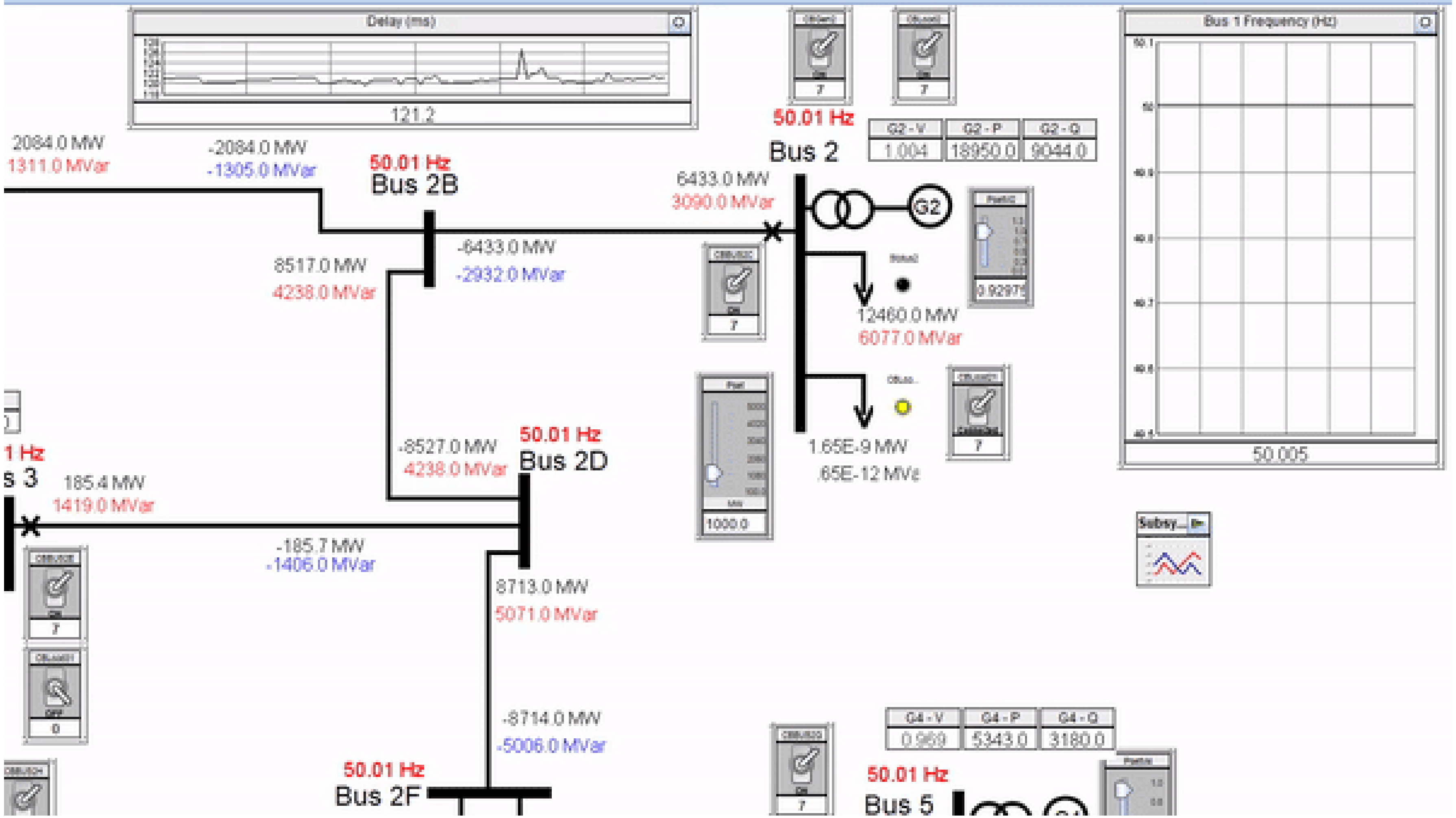
Nokia
Plano, Texas, US

Wide-area control testbed



Frequency control demo

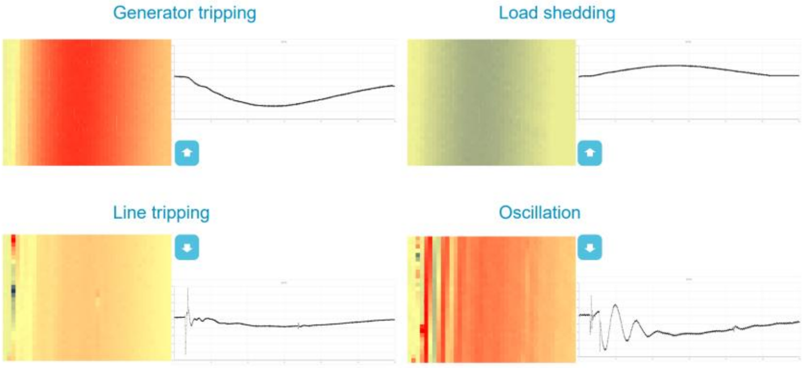
Pre-recorded



At 5x speed

Next steps

- Further performance profiling of ARM devices
- Data analytics using large-scale PMU data
- Wide-area protection and control applications
- Recreate communications delays
- Integrate SV data compression



http://sites.ieee.org/pes-powertech/files/2017/07/PowerTech-2017-Vladimiro-Miranda.pdf

More information

- Contact:
  - steven.m.blair@strath.ac.uk
  - http://personal.strath.ac.uk/steven.m.blair/
  - https://github.com/stevenblair
- Related publications:
  - Measurement and Analysis of PMU Reporting Latency for Smart Grid Protection and Control Applications, https://strathprints.strath.ac.uk/67203/
  - Real-time compression of IEC 61869-9 sampled value data, http://strathprints.strath.ac.uk/57710/
  - Modelling and Analysis of Asymmetrical Latency in Packet-Based Networks for Current Differential Protection Application, http://strathprints.strath.ac.uk/61418/
  - Automatically Detecting and Correcting Errors in Power Quality Monitoring Data, http://strathprints.strath.ac.uk/57466/
  - An Open Platform for Rapid-Prototyping Protection and Control Schemes with IEC 61850, http://strathprints.strath.ac.uk/43427/
  - A Practical and Open Source Implementation of IEC 61850-7-2 for IED Monitoring Applications, http://strathprints.strath.ac.uk/50860/
  - Enabling efficient engineering processes and automated analysis for power protection systems, http://strathprints.strath.ac.uk/54545/
  - Validating secure and reliable IP/MPLS communications for current differential protection, http://strathprints.strath.ac.uk/55961/
  - Demonstration and analysis of IP/MPLS communications for delivering power system protection solutions using IEEE C37.94, IEC 61850 Sampled Values, and IEC 61850 GOOSE protocols, http://strathprints.strath.ac.uk/48971/